WAVEGUIDES AND METHOD OF MAKING THEM

BACKGROUND OF THE INVENTION

Cross-Reference to a Related Application

5   [0001]   Reference is made to copending patent application, filed simultaneously

herewith in the name of Dawes et al. and entitled "PHOTOSENSITIVE MATERIAL

SUITABLE FOR MAKING WAVEGUIDES AND METHOD OF MAKING

WAVEGUIDES UTILIZING THIS PHOTOSENSITIVE OPTICAL MATERIAL."

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10   Field of the Invention

[0002]   This invention relates to optical waveguide devices and a method of

manufacturing optical waveguide devices.

Technical Background

[0003]   Wavelength division multiplexers (WDMs) are designed to separate broad

15   wavelength bands comprised of many discrete narrow band optical signals (individual

channels corresponding to different signal streams) into a number of predetermined

narrow wavelength bands each corresponding to an individual signal channel, at

designated output locations. An example of wavelength division multiplexer is a

phase array device formed in silica based glass. When subjected to changes in

operating temperature, the phase array device shifts the channels into incorrect output locations. The temperature dependent shifts of the channels are caused by index of refraction changes in optical glass, which result in variations in optical path length (OPL) in the phase array.

[0004] More specifically, the phase arrays rely on designed OPL differences to provide a grating effect and to separate, based on wavelength, single broadband input light into several narrow band channels. In such devices, the temperature dependence of the center channel's central wavelength's position arises from the OPL shifts or changes with temperature, which is due to non zero CTE (coefficient of thermal expansion) and the dn/dT (temperature induced refractive index change) of the glass. The central wavelength of the center channel may vary by as much as $0.01 \text{ nm/C}^{\text{o}}$. If the channel spacing were 0.5nm, a 50-degree temperature shift would shift the center channel into an adjacent position. This could result in loss of channels and scrambling in subsequent channel routing. As a result, WDM specifications generally include a thermal stability requirement, allowing a center channel's central wavelength shift of less than 0.05nm over a 70-degree temperature range. In order to overcome the channel shift problem, and to provide the required thermal stability one can utilize a phase array with an actively controlled temperature packaging. However, this approach is relatively expensive and results in large size packaging.

[0005] Passive athermalization for phase arrays requires some form of correction for the temperature dependent OPL shifts. It is known to etch a gap in the phase array of a planar WDM device, creating a separation between the wave guide pairs, and then to fill this gap with an optically transmissive material that has a negative dn/dT. This approach is described in the article entitled " Athermal silica based arrays waveguide

grating multiplexer", Electronic Letters, volume 33, No. 23, pp. 1945-1946, 1997. The dimensions of the gap are such that the light propagating through each arm of the phase array is compensated by having to move through the negative dn/dT material, such that the overall thermally induced optical path length change is zero. However,

5   this approach is also problematic. More specifically, the gap region (with the negative dn/dT material) is lossy due to diffraction through the gap. Loss reduction by using multiple gaps is possible, as disclosed in OFC-98 Technical Digest TU 01-1, pg 204-206, but this has the disadvantage of back reflections and potentially high crosstalk. Loss reduction by formation of slab waveguides, comprised of different index layers in

10   the polymer material situated in the gap is also known. However, such waveguides are difficult and costly to manufacture and compensate only for half of the diffraction induced losses.

[0006]   Fiber to fiber splicing is a critical process step in the fabrication of many devices, and is especially difficult to do when the thermo-mechanical properties of the

15   two fibers are significantly different from one another. Conventional fusion splicing techniques can not be employed for example, for coupling a highly doped amplifying fiber to a silica transmission fiber because during the splicing process the fiber with the lower melting temperature will melt first and fuse to the high melting temperature fiber (silica fiber). When the splice cools down, significant thermal stress builds up in

20   the joint and ultimately causes a fracture. Furthermore, the fabrication of a generic fiber-to-fiber splice requires the two optical fibers to be actively aligned with the ends separated by a distance of about 2μm to about 150 μm. Such fibers are difficult to couple efficiently because the signal light beam provided by the input fiber expands before reaching the second, output fiber, resulting in significant optical loss.

[0007] Thus there is a need for devices that provide efficient light coupling between pairs of optical waveguides, when the two waveguides constituting each pair are separated from one another.

[0008] End-fire curing is the process of sending UV light through the waveguide so that it exits the waveguide and photo-cures (photo-polymerizes) the region which contains photo-polymerizable material and which is located adjacent to the exit face of the waveguide. Such photo-polymerizable materials are one or more monomers with similar diffusion coefficients. These materials tend to further polymerize after the initial exposure, when subsequently exposed to thermal or photo radiation. These materials are susceptible to changes in their index of refraction with time. Thus, there is a need for better photo-curable adhesives.

SUMMARY OF THE INVENTION

[0009] According to one aspect of the present invention a method of coupling optical waveguides comprising the steps of: (i) providing at least one pair of waveguides located such that (a) light radiation propagating through one of the waveguides will be at least partially coupled to a corresponding waveguide and, (b) these waveguides are separated by a gap of about 2µm to about 500µm long; the waveguides having positive dn/dT; (ii) filling the gap with a photo-polymerizable composition, the composition having dn/dT of -2×10^{-4}/C to -4×10^{-4}/C; (iii) providing simultaneous photo-radiation through said waveguides, wherein the photo-radiation photo-polymerizes the composition, thereby (a) creating a first region bridging between the waveguides, the first region having a first index of refraction, and (b) a second region encapsulating the first region, the second region having a second index of refraction, such that said first index of refraction of the first region is at least 0.1% higher than the second index of refraction; and (iv) curing the remaining

composition, while retaining an index difference of at least 0.1% between the first region and the second region. According to a preferred embodiment of the present invention said photo-radiation is in a 180 nm to 400 nm region.

[0010] According to an embodiment of the present invention, a waveguide device comprises at least one pair of waveguides located such that light radiation propagating through one of said waveguides will be at least partially coupled to a corresponding waveguide. These waveguides are separated by a gap of about 2µm to about 500µm and have positive dn/dT. The waveguide device further comprises another waveguide, connecting these pair of waveguides. This connecting waveguide has dn/dT of $-2 \times 10^{-4}/C^o$ to $-4 \times 10^{-4}/C^o$.

[0011] According to an embodiment of the present invention a waveguide device, wherein said pair of waveguides are optical fibers.

[0012] For a more complete understanding of the invention, its objects and advantages refer to the following specification and to the accompanying drawings. Additional features and advantages of the invention are set forth in the detailed description, which follows.

[0013] It should be understood that both the foregoing general description and the following detailed description are merely exemplary of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings illustrate various features and embodiments of the invention, and together with the description serve to explain the principles and operation of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014]   Figures **1A-1E** illustrate schematically the general process for making low loss waveguide couplers. More specifically figure **1A** illustrates a substrate with two optical waveguides and a gap therebetween. Figure **1B** illustrates the gap of Fig. **1A** filled with liquid photo-polymerizable material.   Figure **1C** illustrates the step of providing UV light, from the external sides of the optical waveguide, to the gap. Figure **1D** illustrates the exposure of the top surface of the substrate of Fig. **1B** with UV light. Figure **1E** illustrates the coupled waveguides after the post bake process.

[0015]   Figure **1F** illustrates two aligned optical fibers held by a fixture and seperated by a distance D.

[0016]   Figure **2A** a plot illustrating the dependence of refractive index on temperature.

[0017]   Figure **2B** is a schematic illustration of a planar waveguide array with a substrate containing a trapezoidal shaped gap.

[0018]   Figure **3A** is an enlarged perspective view of two SMF-28™ fibers embedded in photo-polymerized monomer before end fire curing.

[0019]   Figure **3B** is an enlarged perspective view of two SMF-28™ fibers embedded in the photo-polymerized polymer after end fire occurring.

[0020]   Figure **4A** is a schematic illustration of a planar waveguide.

[0021]   Figure **4B** is a schematic illustration of the WDM device.

[0022]   Figure **5A** is a micrograph showing a groove with "bow tie" shaped waveguides, due to excessive pre-cure.

[0023]   Figure **5B** is a micrograph showing loss reducing waveguide, in a gap filled with NOA 63 material.

[0024] Figure **6A** is a micrograph showing the waveguide, in a gap written in a photo-polymerizable composition.

[0025] Figure **6B** is a micrograph showing waveguides in phase array, a gap filled with NOA 63 material.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0026] The general process for making the a coupling device **2** providing low loss

coupling of waveguides is shown schematically in Figures 1A through 1E. More

specifically, waveguides pair **5A, 5B** are etched into a planar substrate **10**. In order to

10 minimize signal loss, the waveguides **5A** and **5B** are aligned so that their optical axis

are preferably co-linear with one another. The substrate **10** is also etched to form a

gap **12** therein. The gap **12** is filled with a liquid photo-polymerizable material **14**

such as a composition curable by UV (ultraviolet) radiation. It is preferred that

refractive index variations with temperature (dn/dT) of this polymerizable material is -

15 $1x10^{-4}$ to $-5x10^{-4}$ and preferably $-2x10^{-4}$ to $-4x10^{-4}$. It is preferred that the material **14**

has a low absorption coefficient of less than 0.5dB, and more preferably, less than

0.3dB/cm at $\lambda=1550$nm. It is preferred that the absorption coefficient of the material

14 be in 0.2dB/cm to 0.3dB/cm range. Such material may be, for example, a

halogenated polymer or combination of different halogenated polymers (including, for

20 example, chlorinated, brominated or florinated polymers). The length D of the gap **12**

between the two waveguides **5A** and **5B** is between about 5μm and about 500μm. In

this embodiment, an ultra violet (UV) light **15** (for example, $\lambda=365$nm) is coupled into

the waveguide array, preferably simultaneously into two opposing sides of the

substrate **10**, to propagate through the waveguides **5A, 5B** and through the UV light

polymerizable material **14** inside the gap **12**. It is preferred that the UV light intensity be about 300 mw/cm^2 or 2 mJ/cm^2 or higher, and that the UV light be coupled into the waveguides **5A**, **5B** for from about 5 minutes to about 3 hours. In this embodiment, the intensity of UV light beam exiting waveguides **5A** and **5B** is about 5 mJ/cm^2. The

5   UV light exiting the waveguides **5A** and **5B** cures and polymerizes the liquid photo-polymerizable material **14** that is encountered in the light path of this UV light, forming an optical bridge **16** between the two sides of the etched gap. Thus, the bridge **16** becomes a waveguiding core in the gap region **12**, such that the signal light entering the coupling device **2** can effectively couple from the waveguide **5A** to opposing the

10   waveguide **5B** or vice-versa. The insertion loss (between waveguides **5A** and **5B**) depends on the lateral alignment of the opposing waveguiding cores and the absorption loss of the photopolymerizable material **14** therebetween. The loss due to a small lateral misalignment of the two waveguides can be minimized by selecting a larger gap. That is, as the gap length D becomes larger, the sensitivity to insertion loss due to

15   small lateral misalignment of two waveguides becomes smaller. Furthermore, in well-aligned waveguides, this insertion loss is not sensitive to the gap length D formation of the coupling waveguide, so long as the photopolymerizable material **14** has a low absorption loss. Thus, the optical bridge **16** improves coupling between waveguides **5A** and **5B** and minimizes insertion losses.

20   [0027]   In a subsequent step, the material **14** in the gap is flood-cured by the UV light. That is, the top surface of the etched gap **12** is exposed by the UV light (same wavelength, lower intensity), to further cure the optical bridge **16** and the remaining polymerizable material **14**, so that optical bridge **16** is supported in the elastic medium. Thus, the optical bridge **16** becomes a core of the waveguide **17** connecting

waveguides **5A**, **5B** and the area **16′** surrounding it becomes its cladding. Finally, to thoroughly cure the polymerizable material **14** in the gap **12** and to provide long term stability, the coupling device **2** is baked at about 100 to 150°C.

[0028] For silicate based waveguides the dn/dT of the waveguides **5A**, **5B** are positive, with a magnitude of about $+1 \times 10^{-5}$/°C, i.e., about a factor of 10 to 40 smaller than the absolute value of dn/dT of the bridge **16**. Thus, the absolute value of the ratio of dn/dT_{bridge} to $dn/dT_{waveguides}$ is about 10 to 40 and preferably about 30 to 40.

[0029] For applications such as athermalizing a planar WDM, the architecture of figure 1D may be advantageous. The optimal path length for the wavelength **5A** and **5B** is now $n \cdot L$ (where n is an index of waveguiding cores and L is their length). When temperature is changed, the change in OPL (called optical path difference or OPD) is $\Delta(nL) \approx \Delta n \cdot L$. It is desired that $\Delta(nL)$ be zero for the waveguide **5A**, **5B** and **16**. Thus, $\Delta n \cdot L$ for the waveguide **16** is $-\Delta n \cdot L$ for waveguides **5A** and **5B**. Therefore, during the thermal shifts the OPL encountered by the signal light propagating through the waveguides **5A**, **5B** is compensated by the OPL induced by the core **16** of the waveguide **17**, thereby athermalizing the device **2**.

[0030] More specifically, it is preferred that two optical fibers **18A**, **18B** be coupled to the input and output waveguides **5A**, **5B** and the UV light is launched through both optical fibers **18A**, **18B** so that the photo-polymerizable material **14** is irradiated by UV from both sides simultaneously. As the UV light exits the waveguides **5A**, **5B**, the two UV beams overlap and the UV light initiates photo-polymerization. The amount of photo-polymerization is proportional to intensity of the UV light. In the photo-polymerized region **16** the index of refraction is higher than in the surrounding region **16′**. More specifically, the core index of refraction (i.e., the index of the bridge **16**) is

higher by at least 0.1% and preferably by 0.3% to 1% than clad index of refraction

(i.e., the index of the surrounding region **16'**). The resultant waveguiding region **16**

has a circular or oval cross-section and improves the optical coupling between the two

silica waveguides **5A**, **5B** across the polymer filled gap.

5   [0031]   A phase array is a coupling device with more than one pair of corresponding

waveguides **5A**, **5B** present in the substrate **10**. In a phase array, the UV beam is

launched into the individual arms of the phase array through waveguides such as a star

coupler. Preferably, the UV beam is launched into the photo-polymerizable material

14 from both sides of each arm in the waveguide simultaneously, and the guided UV

10   light beams initiate photo-polymerization, forming a plurality of bridges **16**. Thus, the

final device has a plurality of waveguiding core regions corresponding to the bridges

16. The resultant waveguiding core regions **16** have circular or oval cross-sections

and improve the optical coupling between the pairs of silica waveguides **5A**, **5B** across

the gap. In a phase array the gap length D between the pairs of waveguides **5A** and **5B**

15   is in the range of 20μm to 500μm is needed to athermalize the device. In several

illustrative examples it was approximately 150μm. During the thermal perturbations

of the phase array, the thermally induced optical path differences encountered by

signal light propagating through the plurality waveguides **5A**, **5B** are compensated by

the optical path differences induced by the core waveguiding core regions **16** of the

20   waveguides **17**, thereby athermalizing the phase array.

[0032]   As stated above, the index of refraction in the photopolymerized region

corresponding to waveguide core regions **16** is higher than in the surrounding regions

16'. These waveguiding core regions **16** couple light from waveguides **5A** into

waveguides **5B**. Without the presence of these waveguiding core regions **16** the signal

light exiting a waveguide such as **5A**, will spread, and only partially couple into the

second, opposite waveguides **5B**, resulting in high insertion loss. Thus, the improved

end-fire coupling process results in formation of an optical waveguide in the polymer

filled gap between the two silica waveguiding regions. The short waveguiding region

5   **16** dramatically reduces the insertion loss and improves overall performance relative to

the device operating with free space propagation through the gap.

[0033]   As described above, a triangular or wedge shaped gap filled with the

photopolymerizable material **14** with the dn/dT value of -1×10^{-4} to -5×10^{-4} and,

preferably, about -2×10^{-4} to -4×10^{-4} is utilized to provide these waveguiding core

10   regions **16**. In order to provide better athermalization, the gap between the waveguide

pairs is wedge shaped, the length of the optical bridges **16** differ from one another.

[0034]   The improved method of coupling waveguides may also be employed in the

making fiber to fiber "splices" by forming a waveguiding core **16** between two aligned

fibers. More specifically, the two fibers **20A** and **20B** are mounted to maintain their

15   alignment relative to one another. In this embodiment (see Fig 1F) the two fibers **20A**

and **20B** are mounted and held by the alignment fixture **22** during the manufacturing

process. The two fibers **20A, 20B** are separated by an air gap that is at least 1μm and,

preferably, about 5μm to about 200μm long. Photo-curable polymerizable material **24**

is then placed into the gap connecting the two facing ends of the fibers **20A** and **20B**,

20   and the UV end-fire curing technique described above is used to photo-cure the

material **24** in the region between these fibers. The photo-polymerisable material **24**

develops increased index on photoexposure due to densification, through crosslinking.

[0035]   Thus, upon initial exposure to intense UV light the material **24** photo-

polymerizes and cross links, forming a high index region **16**, preferably by virtue of a

permanent compositional change (i.e., molecular phase separation). That is, as described in the previous embodiments, during the cross linking process, the exposure to UV light increases the density of the exposed material and thus increases its index of refraction. Subsequently, UV light sets the rest of the material into a polymer within a lower index (clad) region **16'**. As described above, the photo-polymerizable material **24** is chosen for attributes such as dn/dT, absorption loss, index contrast defining the waveguide and the core index of refraction to minimize reflection at the waveguide to waveguide interfaces. More specifically, it is preferred that this material has a reasonably low absorbtion loss (less than 3dB/cm and preferably less than 2dB/cm). The photo-polymerizable **24** has the ability to induce a significant index change about at least 0.05% and preferably, at least, 0.1% and, more preferably, between 0.3% and 1.0% on exposure to UV light with a resultant refractive index of about 1.455 at λ=1550 nm.

[0036] In some of the embodiments the photo-polymerizable material **24** was a commercially available optical adhesive material such as NOA (Norland Optical Adhesive) 81 or NOA 63, available from Norland Products, Inc. of Cranbury, NJ. These adhesive materials are not preferred because subsequent exposure to the UV light or to heat may further polymerize the cladding region **16'**. This reduces the difference in refractive indexes between the core region **16** and clad region **16'**. Thus a coupling device that uses one of these adhesive materials needs to be packaged to shield the polymerized regions **16** and **16'** from the excessive thermal or photo exposure.

[0037] Applicants have developed a more preferable photo-polymerizable composition, which undergoes a permanent compositional change during UV exposure. In this

composition several components were mixed to form the photo-polymerazable liquid that, upon exposure to UV light, forms the core/clad waveguide structure **17**. This composition includes (a) a slow curing component I (a polymer) with low diffusion coefficient (of about 10^{-8} cm^2/sec to about 10^{-10} cm^2/sec) and with low index of

5 refraction, (b) a fast curing component II (a monomer) with high diffusion coefficient (of about of about 10^{-5} cm^2/sec to about 10^{-8} cm^2/sec) and high index of refraction, and (c) a component III (a di-functional monomer) that improves the compatibility of components I and II by binding to both compositions I and II to prevent phase separation and promote the stability of the cured polymer structure. The composition

10 may also include two photo initiators. The first is a radical initiator and the second is a cationic initiator. These initiators, together with components I, II, and III can generate a large refractive index difference, upon completion of the curing process, between waveguiding core region **16** and the cladding **16′**. More specifically, upon exposure to a localized beam of UV light (about 185nm to about 500nm) the component (II)

15 polymerizes and densifies, forcing the low index component (I) away from the beam path. The resulting cured region has a high index of refraction, and can, thus, act as a core **16** in a waveguiding structure. In a second step the entire gap is dosed with a relatively low intensity flood illumination of UV radiation. In this step, both components (I) and (II) are polymerized into a relatively low index co-polymer

20 (compared to the core), which serves as a cladding **16′** in a waveguiding structure.

[0038]   In this example, the first component (I) is a cationic polymerizable fluorinated solid polymer with a relatively low refractive index (1.43-1.47). It is preferred that this component (I) be a fluorinated aleimide/fluorinated acrylate/glycidyl methacrylate with a

linear coefficient of thermal expansion of about 30-80 ppm/°C. It is more preferable that

the linear coefficient of thermal expansion be about 30-60 ppm/°C.

[0039]   Due to this component's highly fluorinated structure, it readily phase separates

from the hydrocarbon monomers that comprise the rest of the formulation during

5   photopolymerization. Thus, this component (I), due to its slow reactivity during the

UV curing process at room temperature, flows away (by diffusion) from the cured high

index region **16** and forms a part of the low index cladding **16´**. Component (I) is

described in more detail in a related US patent application serial no. 09/704,116 filed

on November 1, 2000, which is incorporated by reference herein.

10   [0040]   Component (II), is a high index and highly reactive hydrocarbon liquid

monomer. This component is commercially available. An example of suitable

component II is diacrylate or dimethacrylate. This component (II) will be polymerized

in the path of the localized UV beam (i.e., the UV beam exiting through the

·waveguides **5A, 5B**) because of the high UV reactivity and high diffusion coefficient

15   compared with the composition (I).

[0041]   The third component (III) is small amount of di-functional monomer that can

bond directly to both component I and component II. This di-funcational monomer

can be polymerized by radical and cationic polymerization. One example of such

monomer is glycidyl methacrylate. When reacted with components (I) and (II)

20   initiated by a non-localized UV irradiation, such as during the flood exposure, it

reduces the tendency for component I and component II to phase separate, resulting in

an optically transparent, relatively low index co-polymer. The final structure of the

entire composition is an interpenetrating polymer network (IPN). Specifically, the

photo-polymerisable material providing a compositionally stable core/clad structure, was formulated as follows.

EXAMPLES

[0042] In an experimental example, one gram of fluorinated maleimide/fluorinated acrylate/glycidyl methacrylate copolymer (composition (I), index =1.462 at 1550 nm) was dissolved into 1.5 grams of composition (II) 1-4 butanediol dimethacrylate, homopolymer (with the index of refraction in a 1.50-1.51 range at 1550nm) and 0.3grams of glycidyl methyacrylate (composition (III)) on the hot plate at a temperature of about 60 °C. Upon dissolution, 26 mg of cationic initiator (triaryl sulfonium hexafluoroantimonate salts) and 21 mg radical initiator (Radocur 1173 ™) were added into the liquid formulation. The clear solution was coated to the ends of the optical fiber, such as Corning's SMF-28™ optical fiber. After curing under the UV lamp (λ = 365nm) for ten seconds (120 mJ/cm^2), the entire composition was post-baked at 150 °C for 15 minutes. Measuring the reflection light intensity of the fiber/polymer interface at a temperature between about 30°C ad 200°C, we obtain the value of dn/dT and corresponding glass transition temperature of cured material (see Figure 2A). The results from the plot showed a glass transition temperature of about 160 °C and the dn/dT about -2.12 x 10^{-4} between the temperature range of 30-140 °C. The average refractive index of the core of the connecting waveguide at 20 °C is 1.493. These attributes make this photo-curable composition appropriate for low loss end fire waveguide coupling applications.

Process for fiber-to-fiber coupling

[0043] We used the following procedure to write a waveguide between two single mode SMF-28™ fibers. First, the fibers were stripped of the coating and cleaved with a

90 degree flat cleave angle utilizing a standard fiber cleaver, such as Ericcson™ EFC

II fiber cleaner or Siecor® FBC-006 high precision fiber cleaver, for example. Next,

the cleaved fibers were placed in a precision XYZ stage to control the alignment of the

fibers. A gap of approximately 75 microns was left between the two fiber ends. A

5   drop of NOA 81 UV curable optical adhesive (available from Norland Products, Inc.

of Cranbury, NJ) was placed into the gap directly adjacent to the facing ends of the

fibers and the fibers were actively aligned at 1550nm to optimize the alignment of

their cores (see Figure 3A). The UV curable adhesive was flood cured from above

(i.e., the entire region between the fibers was irradiated with UV using a UV spot

10   curing source or lamp) with a low intensity (less than 10mW/cm^2) UV lamp for

30seconds to pre-gel (partially photo-polymerize) the adhesive. In this example, the

intensity of UV light was about 3mW/cm^2.

[0044]   The flood-curing step raises the viscosity of the material and, therefore,

increases the rigidity of the material. Without this step, the light coming out from the

15   end of the fiber will locally cure the adhesive forming the core of the waveguide. This

core would be situated in the un-reacted liquid adhesive and will eventually deform

due to convection currents produced in the liquid matrix. After pre-curing (also

referred as pre-gelling), high intensity UV light (λ =365nm) from, for example, a

Greenspot UV source (1200mW/cm^2 at λ = 300-400 nm) was launched, from the

20   source towards the external ends of both fibers, simultaneously, for two minutes to

write the waveguide between the two fibers. The resulting written wavegulde region

16 is shown in Figure 3B.

[0045]   We demonstrated improved optical coupling between two SMF-28™ fibers

using the UV end-firing curing technique. This technique was used to couple two

SMF-28^{TM} fiber ends that were clad aligned with a gap of 150μm between them. Before the waveguide was written between the two fibers, the insertion loss (IL) was 4.68 dB. After the waveguide was written the insertion loss was 1.37dB, an improvement of 3.4dB.

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Process For Writing Waveguide in a Gap of a Planar Waveguide Device

[0046] The following process was utilized to write a coupling waveguide in a gap between two arms of a planar waveguide 25 and to analyze the insertion loss before and after this coupling waveguide was made. It is noted that more than one coupling

10 waveguide can be simultaneously made by this process.

[0047] A photopolymerizable material is placed into the gap between opposing pairs of waveguides and the insertion loss is measured prior to forming the coupling (i.e., connecting) waveguides in this gap. The insertion loss is measured at 1550 nm by close coupling two fibers 30A, 30B to the ends of the straight waveguide 5A, 5B and

15 measuring the power relative to a straight waveguide with no gap (see Fig. 4A). The cure process involved the following steps:

1) Pre-cure the material in the gap with a flooded low power UV source (180 nm < λ < 450 nm; and power of 5-10 mw/cm^2) to increase the viscosity of the material. In this example the wavelength of UV source was about 365nm and the

20 power was 10mW/cm^2. The actual pre-cure time will depend on the intensity of UV light source and the distance between the UV light source and the gap. The pre-cure time will usually be between 1 second and 1 hour, with a preferable time of about 4 seconds to about 0.5 hr.

2) Launch UV light (λ=365nm) through the waveguides, by coupling the UV light

through SMF-28™ fiber. This step will "end-fire" cure the material between the two opposing arms of the waveguides, thereby writing a connecting waveguiding core therebetween.

3) Thermally postcure to rigidize the entire matrix (cladding and core) of the coupling waveguides. The typical past cure temperatures are 0.5 hr. to about 3 hours at temperatures of about 70°C to about 250°C. In these examples the post-cure times were 120°C for about 15 minutes and 70°C for one (1) hour.

[0048] Finally the insertion loss at λ=1550 nm was measured again in order to determine the waveguide efficiency in reducing loss from the free space propagation value. It was determined that the insertion loss decreased after the waveguide was written.

[0049] Several experiments using the above described end-fire curing process in order to write waveguides in a polymer filled gap are presented here. These experiments succeeded in demonstrating nearly total elimination of insertion loss due to diffraction. More specifically, we utilized a planar waveguide array with straight waveguide pairs. This waveguide array had 60 pairs of straight waveguides. The length of this waveguide array was 2.2 cm and the spacing between the waveguides was 40 microns. The waveguide pairs were separated by an etched trapezoidal gap as shown in figure 2B. The gap at the wide and narrow ends measured 140nm and 20nm long, respectively. The difference in the gap length between each adjacent successive waveguides was 2 microns. Free space propagation through the gap causes a gap length (D) dependent loss (Loss) which for an index oil filled gap (n=1.45) is described by the following equation:

$Loss_{oil}$= (Coupling Loss) + (Propagation Loss)$_{oil}$ + 0.047dB (D- 16 μm). If a coupling waveguide is written between the two separated waveguides W, then the total insertion loss is independent of the gap length D and is described by the following equation.

LossWaveguide= (Coupling Loss) + (Propagation Loss)$_{waveguide}$

[0050] When the experiment was run, the power transmission was measured by close coupling of two fibers to the ends of the waveguide **5A, 5B** before and after the writing of the coupling waveguide there between. The improvement in power transmission was compared to the gap length dependent insertion loss to determine the efficiency of the waveguide. For the above described device the coupling loss plus propagation loss (i.e., material absorption loss) is about 0.8 dB +/- 0.3 dB, based on uninterrupted straight waveguide (i.e., a 2.2cm waveguide device with no gap) measurements.

[0051] End fire curing through a complete phase array was performed on a 1 x 8 phasar device incorporating two star **35A, 35B**. The results successfully indicated that a single end-fire cure process could simultaneously write waveguides across each of the arms in a phase array. This device is illustrated in Figure 4B.

[0052] Several examples of varying process conditions to write waveguides in the groove indicate the process parameters, and potential for this technique. The pre-cure (pre-gel) step was found to be important in achieving lowest possible loss.

[0053] Figure 5A shows a sample made under good pre-cure conditions, using a fast curing photo polymerizable optical adhesive (NOA 63 available from Norland Products, Inc., of Cranbury, NJ) in the gap. This adhesive was pre-cured for eight (8) seconds by illumination with 10 mw UV source from a distance of about 2 cm, and then end-fire cured for one hundred twenty (120) seconds at room temperature equal to 23°C. The formed waveguide was straight and confined. When this procedure was

repeated without a pre-cure step (pre-cure time = 0 seconds), no reduction in loss was measured and the waveguide shape was deformed.

[0054] Figure 5B shows an example of a sample that was pre-cured for too long before end-fire curing. The gap was filled with another fast curing photo polymerizable optical adhesive, NOA 81 (also available from Norland Products, Inc.), and was pre-cured for 30 seconds and end-fire cured for 20 minutes. Here a "bowtie" pattern was formed in the polymer, the result of the UV beam divergence across the entire gap width from both waveguides. The loss improvement measured in this example was only 0.7dB relative to a gap width dependent loss of 4.8 dB. The examples show how the above described process results in improvements of loss and how the pre-curing step results in better quality of waveguides formed by the end-fire curing process.

[0055] Fast, photo-currable multi-component optical adhesive F1, manufactured by Corning Inc., was then utilized to form low loss coupling waveguides that could provide excellent stability upon exposure to subsequent UV and heating. This adhesive was processed by coincident flood illumination and end-firing for 300 to 600 seconds. The waveguide device was then heated to 100°C for 1 hour to thermally cured and rigidize the device. Figure 6A shows a waveguide formed with the 300 second cure, through D = 96 μm. The resultant index contrast of a written waveguide is about 1%. Then the propagating mode is well confined in the waveguide, contributing to the low insertion loss. The formed waveguide is stable as the index gradient is defined by a cone that is depleted in the low index material. Such a structure cannot be bleached optically or thermally. The loss improvement measured for this example was 3.6dB. That is, the formation of coupling waveguide recovered nearly all of the original 3.7dB diffraction loss.

Table 1. Data for the waveguide writing embodiments described above

	Example 1	Example 2	Example 3	Example 4
Polymer	UV3000	NOA 81	NOA 63	F1
Loss calculator from D	4.8	5.1	3.7	3.7
Loss Measured $_{oil}$	4.8	4.8	3.6	3.7
Loss after endfire cure	>5	4.1	0.9	0.1
Improvement	None	0.7	2.7	3.6
Process	End cure only, no pre-cure	Pre-cure End cure 20 min	Pre-cure 8 seconds End cure 60 seconds	1) Simultaneously Co-cure top and fire end cure for 300 seconds

[0056]   Finally, coupling waveguides within a trapezoidaly-shaped gap were written in a phase array utilising the method described above. The major difference between the phase array compared to those previously described devices is that when the UV source is launched into the input and output waveguides, the light follows a path that first enters a slab waveguide with free space propagation before impinging on the phase array, a group of 50 to 100 waveguides that perform the grating function in the device. For a given incident power, the actual UV signal crossing any one path across the gap has about 1 to 5% of the original power. Figure 6B shows an optical micrograph of the phase array region filled with NOA 63, and exposed for 1 hour using multimode fiber end-fire curing (maximize UV power coupling into the planar waveguides), with low intensity flood curing. The micrograph shows a region in the gap phase array where 10 waveguides were written with the single exposure.

[0057]   The process described here was developed in response to needs arising from athermalization of phase array WDM devices and fiber to fiber splicing. The key elements are that a low cost process is used, and low optical loss can be achieved. In the case of the phasar devices this technology could be used to athermalize the output wavelength positions. In fiber to fiber splicing this technique can be used to couple

light between fibers with significantly different material properties, where fusion splicing is difficult to impossible. Other applications can be easily envisioned as falling within the scope of the invention. Thermo-optic devices made by replacing a section of silica planar waveguides, for example in one arm of a Mach Zehnder device, with UV waveguidable polymer with large negative dn/dT could be used to maintain low loss and to reduce switching power by a factor of 25. Issues with multiple gaps in a single pass would have to be addressed. Also the potential of reducing coupling loss in fiber to fiber bonds where the two fibers have poor mode field match characteristics could have significant utility.

[0058]   Accordingly, it will be apparent to those skilled in the art that various modifications and adaptations can be made to the present invention without departing from the spirit and scope of the invention. It is intended that the present invention covers the modifications and adaptations of this invention as defined by the appended claims and their equivalents.